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Factors Affecting the Dissolution of Gypsum-Bonded Roof Bolts

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	L/d	liter per day
°C	degree Celsius	min	minute
ft	foot	mL/hr	milliliter per hour
g	gram	pct	percent
g/d	gram per day	ppm	part per million
$g/d \cdot L^{-1}$	gram per day per liter	rpm	revolution per minute
g/hr	gram per hour	sec	second
g/L	gram per liter	sq cm	square centimeter
g/min	gram per minute	yr	year
L	liter		

FACTORS AFFECTING THE DISSOLUTION OF GYPSUM-BONDED ROOF BOLTS

By S. J. Gerdemann [1] and J. S. Hansen [2]

ABSTRACT

In support of its objective to improve mine safety, the Bureau of Mines has searched for better materials and systems to anchor roof bolts. This report describes a study on the effects of mine waters upon accelerated gypsum, one of the materials under consideration.

The accelerated gypsum dissolved at an appreciable rate relative to an assumed 10-yr life span of a roof bolt. Surface orientation, initial ion concentration of a dissolving solution, and flow rate of the solution had substantial effects on the dissolution rate. Factors such as water-cement ratio, accelerator content, wax capsule additions to the gypsum in cartridge-installed bolts, surface area, temperature, and curing duration had little effect.

In an actual roof-bolt environment, dissolution will occur in static solutions to the solubility limit of gypsum (~2 g/L) and cease, resulting in minimal damage; but in flows of unsaturated solution as slow as 1 L per month, a loss of up to 10 pct will occur in 2 yr. Since miners cannot readily measure the flow or ion concentration of static-appearing water at every roof-bolt site, all such water must be assumed to be pure and flowing. It is recommended that gypsum-bonded roof bolts be confined to dry roofs only.

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INTRODUCTION

It is established practice to use roof bolts to support roofs and ribs in coal, metal, and nonmetal mines. The most commonly used bolt is mechanically anchored at the end opposite the bolthead by a device that contacts the hole wall when the bolt is tensioned. Through tensioning, the layers of rock between the bolthead and anchor are tied together to form a "beam" that supports itself as well as the rock above it.

In 1972, an innovative bolting system was introduced that relied upon polyester resin to bond the bolt to the rock along its entire length.[3] Among its advantages, the fully anchored bolt provided excellent resistance to roof shear and to high induced tension in the presence of roof parting. Although by no means dominating the market, more than 20 million full-column bolts were installed in 1980. The major drawback to its more widespread use has been cost.

In accord with Bureau of Mines goals to improve the safety of mines and mining, the Bureau's Spokane (WA) Research Center conducted a search for new, lower cost bonding materials to substitute for polyester resins as an anchoring medium.[4] Because high early strength was also a criterion, many common cementitious materials, such as portland and aluminate cements, were rejected early in the search. The cement showing the most promise was composed of calcium sulfate hemihydrate ($CaSO_4 \cdot 1/2H_2O$) and a small amount of potassium sulfate (K_2SO_4) accelerator, which upon hydration forms primarily gypsum. Apparently meeting all criteria, the accelerated gypsum was low cost, nontoxic, and fast setting, and developed more than adequate strength in less than 5 min.

Two systems were developed for installing roof bolts with the new cement. In one, water and accelerated hemihydrate are injected simultaneously into a roof-bolt hole and a roof bolt is installed. Within 10 to 20 sec, the hardening reaction begins to set the bolt. In the second system, referred to as the cartridge system,[5] the accelerated hemihydrate is blended with water capsules and placed into a long plastic bag. Each water capsule consists of less than a drop of water that is surrounded by a thin wax shell. The cartridge is inserted into a hole, the bolt is installed, and the bag and water capsules rupture, initiating the hydration reaction and hardening. Visible success has been achieved during in-mine tests of both systems. However, since gypsum is slightly soluble (2.22 to 2.41 g/L), suspicions have been expressed concerning the ability of either system to remain intact and support a roof in a wet mine environment over a period of years.

The solubility of gypsum is acknowledged; however, little is known about the rates at which gypsum dissolves. For instance, powdered gypsum will dissolve to the solubility limit almost instantaneously in stirred water, while a flat mass, lying horizontally, might take days or weeks to dissolve in still water. The dissolution rate may be further complicated if the dissolving solution contains gypsum or one or more of several sulfates. The orientation of a gypsum mass also has an effect on dissolution rates—the same flat mass will dissolve faster in a vertical position than in a horizontal position.

[3]Gerdeen, J. C., V. W. Snyder, G. L. Viegelahn, and J. Parker. Design Criteria for Roof Bolting Plans Using Fully Resin-Grouted Nontensioned Bolts To Reinforce Bedded Mine Roof (contract JO366004, Michigan Tech. Univ.). Volume 1. Executive Summary and Literature Review. BuMines OFR-46(1)-80, 1977, 208 pp.; NTIS PB 80-180052.

[4]Simpson, R. E., J. E. Fraley, and D. J. Cox. Inorganic Cement for Mine Roof-Bolt Grouting. BuMines RI 8494, 1980, 32 pp.

[5]Simpson, R. E. (assigned to U.S. Department of the Interior). Cartridge for Grouting an Anchor Element in a Hole of a Support Structure. U.S. Pat. 4,096,944, June 27, 1978.

EXPERIMENTAL

Two tests were developed to simulate and quantify the dissolution of gypsum in wet mines under a range of damaging conditions that could be encountered. The fastest possible dissolution in a mine was assumed to occur when a moving stream of pure water is in contact with the gypsum-bonding medium of a bolt. Conceivably, this situation might be encountered if a crack developed in a seam and connected the roof bolt to an aquifer. The rapid dissolution environment was simulated by small gypsum specimens in tanks of slowly stirred pure water. The slowest possible dissolution in a mine, except for a completely dry environment, was assumed to occur when a small quantity of static solution at high ion concentrations is in contact with the gypsum. This condition was simulated by specimens in tanks of static solutions containing several ionic species.

Gypsum specimens for both types of tests were prepared by blending calcium sulfate hemihydrate powder (referred to generically as plaster) with potassium sulfate accelerator. The blended plaster was added to distilled water at predetermined water-cement ratios and stirred with a drill-motor-driven mixing shaft at 1,200 rpm for 10 sec. The resulting paste was poured into six to eight 0.8- by 9.2-cm petri dishes and settled on a vibrating table for 2 min to remove air. The nominal weight of each specimen was 100 g. Because the petri dish was not removed, the area of the exposed gypsum was about 67 sq cm.

Only smooth-surfaced specimens were used for the stirred tests. These specimens contained either 0 or 1.5 pct accelerator and water at water-cement ratios ranging from 0.300 to 0.400. The tests were initiated by placing a petri dish specimen, with the gypsum surface facing up, into a stainless steel vessel containing 2.5 L of distilled water that was stirred at 50 rpm. Two tests under like conditions were run concurrently, as shown in figure 1. The calcium ion concentration in solution was measured with a calcium-specific ion electrode and millivoltmeter. The electrode was allowed to stabilize in solution 5 min before a measurement was taken. Measurements were taken at 10-min intervals alternately between the two tests; that is, the calcium level in each solution was monitored every 20 min. The data from the electrode in parts per million were then converted to a specimen weight loss.

The specimens for static tests were cast at a constant water-cement ratio of 0.400 and at an accelerator level of 1.5 pct, using the same procedure described for stirred tests. The high water-cement ratio was chosen because the resulting specimens were more uniform and water-cement ratio had not had a significant effect upon dissolution in the stirred tests. Following casting the specimens were dried at 45° C overnight, ground on a belt sander, finish-sanded on 400-grit silicon carbide paper, and washed. The specimens were redried at 45° C for at least 2 days or until a steady weight was reached. After cooling and weighing, 6 to 10 specimens were placed, with the gypsum surface facing up, in individual covered beakers containing 1.0 L of solution. Upon completion of the test after a selected time interval, each specimen was dried and weighed. Although the calcium-specific ion electrode was a fast and reproducible instrument for measuring gypsum in the stirred tests, it proved unsuitable for static tests. In static solutions, the ion concentration is nonuniform, making such measurements meaningless. Consequently, the amount of gypsum dissolved in all static tests was determined by direct weight loss measurements of the dried specimens.

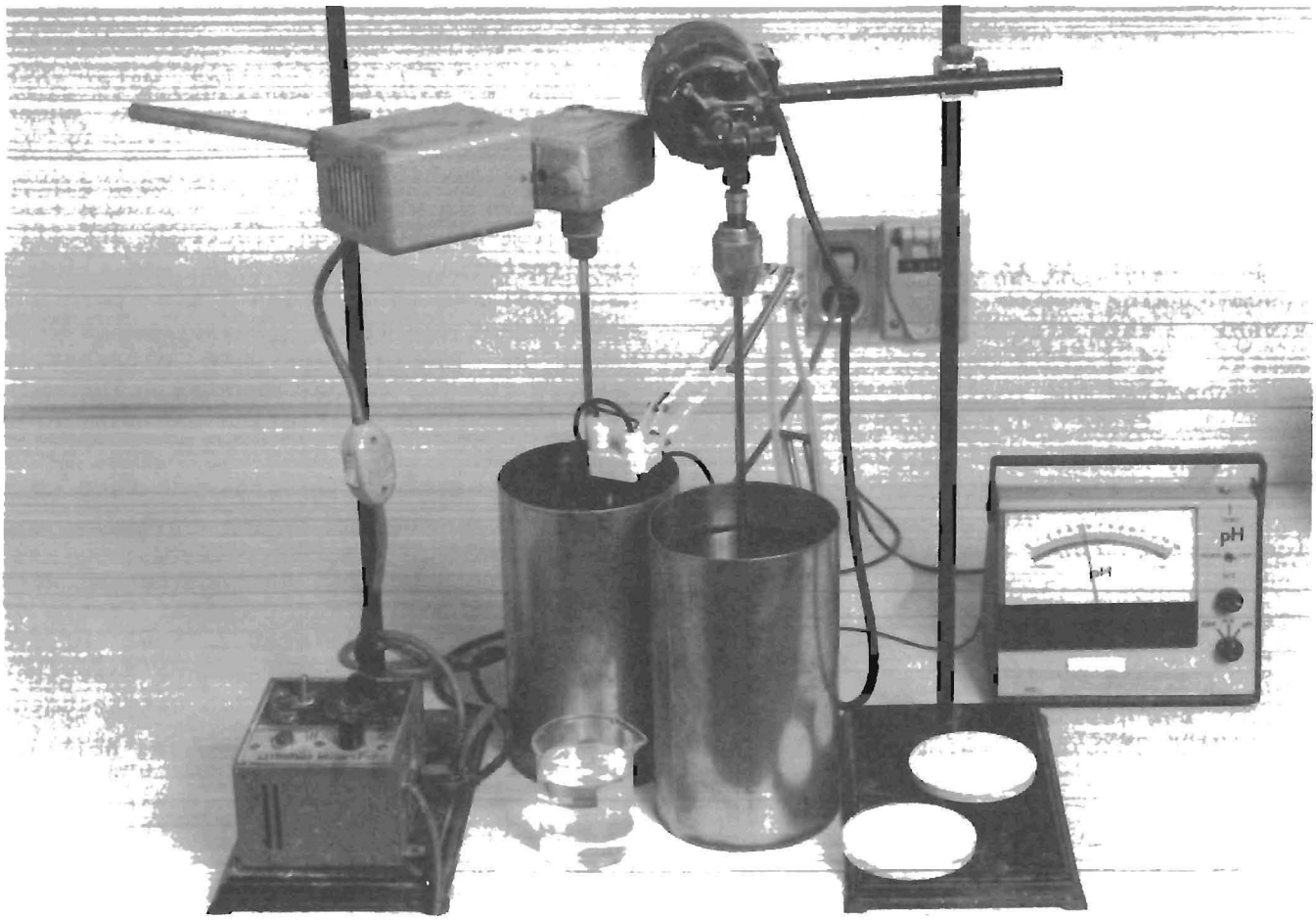

FIGURE 1. - Apparatus to measure gypsum dissolution under stirred conditions. Petri dish specimens are shown at lower right.

RESULTS AND DISCUSSION

STIRRED-SOLUTION TESTS

Stirred-solution tests were used to define the effect upon gypsum of water-cement ratio, drying time, and accelerator level. Additional tests were run on small samples from simulated roof bolts that contained wax capsule remnants as well as gypsum. An example of the type of data obtained is plotted in figure 2. Note that the gypsum missing from the petri dish is expressed as a weight loss, and that the experimentally determined points are more scattered at high weight losses corresponding with solutions that approach saturation. The effect of surface area was ignored because it was immeasurable over the limited area differences that were investigated. The specimens used to calculate this and other curves weighed 100 g, and the losses from larger masses of similar content and geometry can be computed by multiplying the data by each multiple of 100 g in the mass.

The variation of gypsum dissolution with curing duration, timed from the moment of hydration, is shown in figure 3. Dissolution was slightly slower at a curing duration of 30 min than at longer durations. Beyond 1 day, curing duration had no effect on dissolution. The variation of gypsum dissolution at four water-cement ratios is plotted in figure 4, and the variation of gypsum dissolution at two levels of accelerator is plotted in figure 5. Variations in water-cement ratio and accelerator content, like those in curing duration, did not cause significant increases or decreases in the dissolution rate.

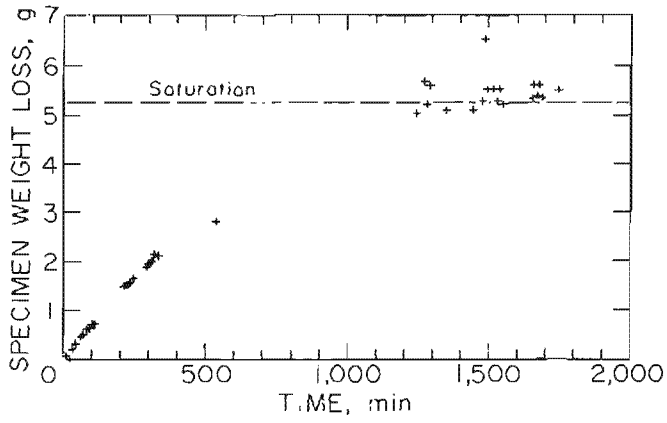

FIGURE 2. - Typical dissolution of cast gypsum (100-g specimen) in 2.5 L of slowly stirred water.

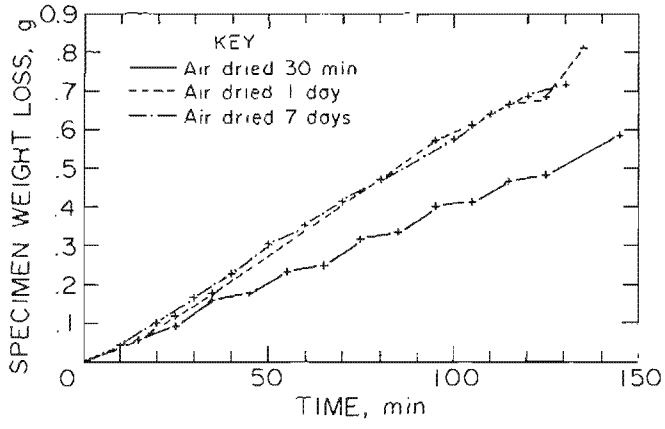

FIGURE 3. - Variation of gypsum dissolution with curing duration. Stirred water, 0.375 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

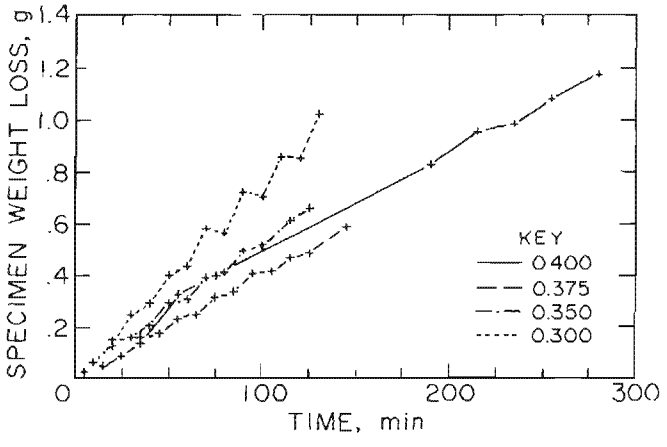

FIGURE 4. - Variation of gypsum dissolution with water-cement ratio. Stirred water, 1.5 pct accelerator, 30-min duration, 100-g specimens.

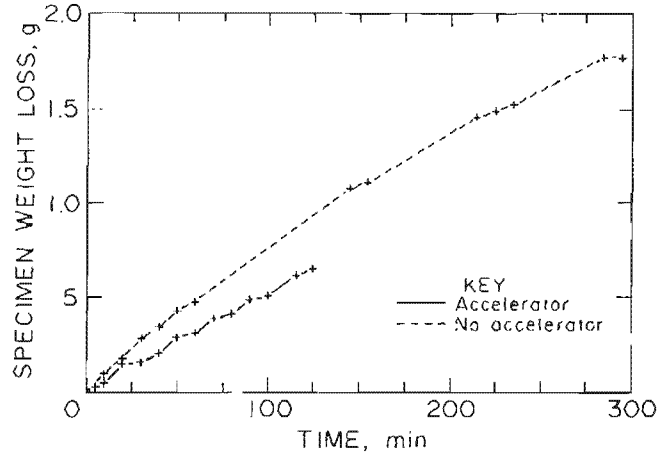

FIGURE 5. - Variation of gypsum dissolution with accelerator level. Stirred water, 0.350 water-cement ratio, 30-min curing duration, 100-g specimens.

A weight loss per hour was estimated from the data in figures 3 and 4 by assuming linearity. These estimates are compiled in table 1 and plotted in figure 6 as a weight loss rate from the petri dish specimens.

In a roof-bolt environment, slight changes in either curing duration or water-cement ratio, of the magnitude noted in table 1, would not slow dissolution by more than 9 days per 100-g mass before complete deterioraton resulted. Of course, dissolution would slow as the solubility limit of the solution (~2 g/L) is approached, and rapid deterioration would result only if the environment surrounding a roof bolt contained the equivalent of 2.5 L/d of fresh, moving water.

TABLE 1. - Rate of gypsum dissolution at various curing durations and water-cement ratios[1]

Cure duration	Water-cement ratio	Weight loss, g/hr
30 min.....	0.400	0.248
	.375	.239
	.350	.311
	.300	.453
1 day.....	.375	.355
	.350	.317
	.300	.450
3 day.....	.400	.235
7 day.....	.400	.228
	.375	.343
	.350	.372
	.300	.343

[1]Conditions: 100-g specimen, 1.5 pct K_2SO_4 accelerator, air cured, immersed in 2.5 L water, stirred at 50 rpm.

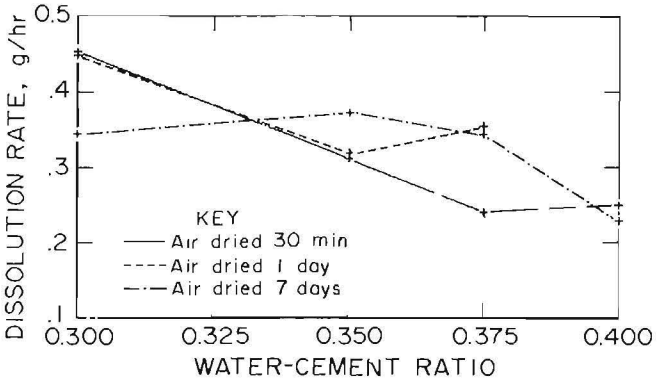

FIGURE 6. Dissolution rate of gypsum as a function of water-cement ratio at three curing durations. Stirred water, 1.5 pct accelerator, 100-g specimens.

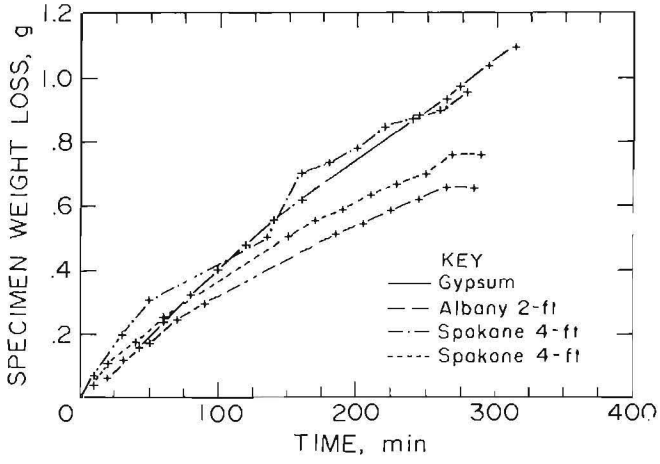

FIGURE 7. - Dissolution of several wax-containing roof-bolt gypsum samples compared with cast gypsum. Each sample weighed 100 g.

Stirred-solution tests were also done on samples (retrieved from mine simulations of the cartridge roof-bolting system) that contained both gypsum and remnants of wax capsules. After installation, the wax had remained distributed throughout the gypsum and amounted to between 23 and 29 pct of the volume. Because the wax appeared to coat the gypsum crystals and, in some instances, to modify the crystalline structure, it was initially thought that the wax might also protect the gypsum from dissolution. To test this hypothesis, samples were taken from two 4-ft and one 2-ft simulated roof bolts that had been installed at a water-cement ratio of 0.319. (The 4-ft bolts had been installed at the Spokane Research Center, and the 2-ft bolt at the Albany Research Center.) The dissolution test data on these samples were compared with data on a small piece of cast gypsum. The curves shown in figure 7 demonstrate that the roof-bolt gypsum was similar to the cast gypsum relative to dissolution rates, and that the roof-bolt gypsum dissolved at a rate only slightly slower, $<1 \times 10^{-3}$ g/min, than the cast gypsum.

STATIC-SOLUTION TESTS

Static-solution tests were made to define the effect upon gypsum dissolution of several ions that might be present in mine waters. The Ca and SO_4 ions of gypsum itself were the first ionic species

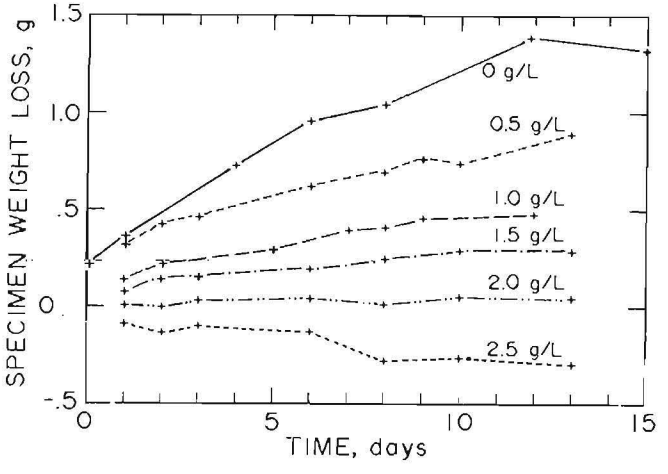

FIGURE 8. - Variation of gypsum dissolution with initial solution concentration of gypsum. Static solution, 0.400 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

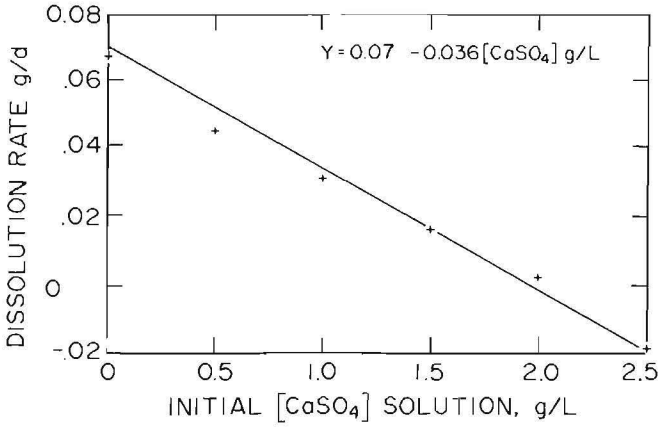

FIGURE 9. - Variation of the rate of gypsum dissolution (for 100-g specimens) with initial sulfate ion of gypsum in solution.

TABLE 2. - Simulated mine water solutions, total sulfate concentrations, and gypsum[1] dissolved in each per day

Solution	SO_4^{2-} concentration, g/L	Gypsum dissolution, $g/d \cdot L^{-1}$
Distilled water.....	0	0.77
Distilled water adjusted to pH 3 with H_2SO_4.....	.048	.074
Distilled water with 100 ppm $Fe_2(SO_4)_3$ and 100 ppm $MgSO_4$.	.650	.059
Distilled water adjusted to pH 3 with H_2SO_4 and 100 ppm $Fe_2(SO_4)_3$ and 100 ppm $MgSO_4$.	.700	.042

[1]From 100-g specimens.

investigated. Accordingly, gypsum was added to test solutions, in increments of 0.5 g/L, up to 2.5 g/L. As shown in figure 8, the rate of dissolution decreased with increasing initial solution concentration of gypsum. Specimens lost little weight in solutions close to saturation and gained weight in supersaturated solutions. When the rates of gypsum dissolution (the slopes of the curves in figure 8) were plotted against the initial solution concentration, a straight line resulted that is expressed by the equation

$$Y = 0.07 - 0.036\ CaSO_4\ g/L. \quad (1)$$

This line, depicted in figure 9, shows that at a rate of zero dissolution, the initial solution must contain ~2 g/L of $CaSO_4$, agreeing closely with the theoretical value. If the initial concentration of gypsum in any solution is given, values from the graph can be used to calculate a rate of dissolution. Figure 9 also shows that compared with dissolution in stirred solutions, as shown in figure 6, dissolution in static solutions is slow.

In a second series of static tests, gypsum dissolution rates were measured in solutions containing other ionic combinations that might be found in mine waters. The ions studied are shown in table 2, and the variation of gypsum dissolution with sulfate ion concentration in simulated mine waters is shown in figure 10. The initial concentration of sulfate ion also had an inverse effect upon the dissolution rate, similar to the effect of the ions of gypsum. The variation of the rate of gypsum dissolution with sulfate ion concentration is plotted in figure 11 and is independent of the cation species of the sulfate-containing compound.

The solubility of gypsum is also affected by temperature. However, in the range of temperatures (between 4° and 55° C) that is normally encountered in mines, the solubility, as shown in

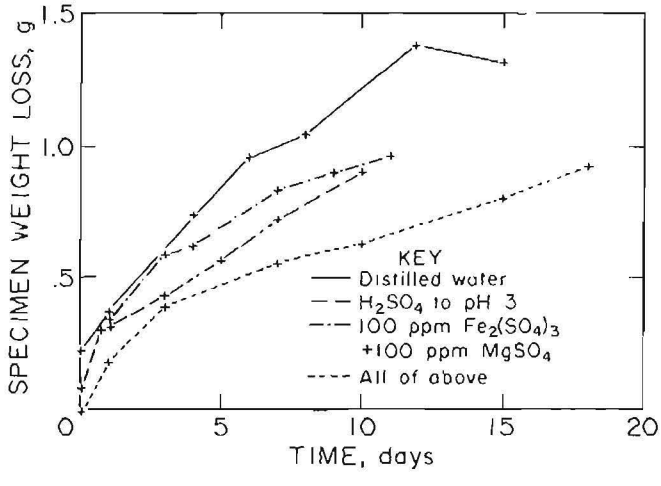

FIGURE 10. - Variation of gypsum dissolution with sulfate ion concentration in simulated mine water. Static solution, 0.400 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

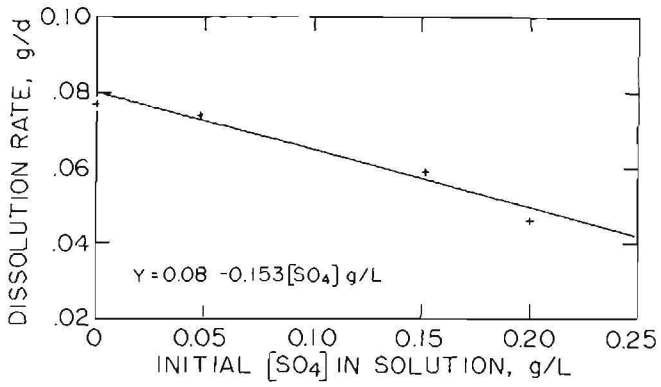

FIGURE 11. - Variation of the rate of gypsum dissolution (for 100-g specimens) with initial sulfate ion in solution. The variation is independent of the cation of the sulfate-containing compound added.

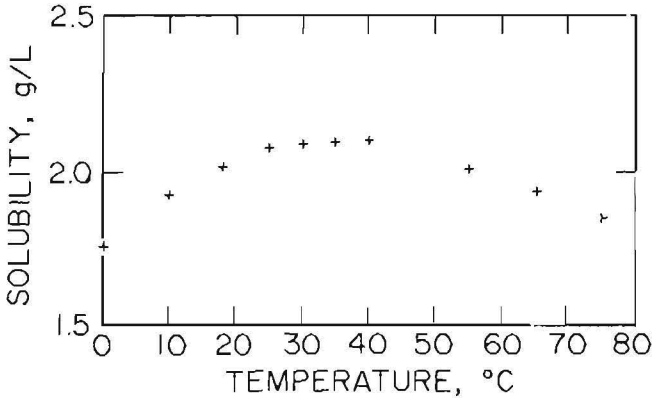

FIGURE 12. - Variation of gypsum solubility with temperature. (Based on data from "Solubilities of Inorganic and Metal Organic Compounds," by A. Seidell and W. F. Linky. Van Nostrand, New York, v. 1, 4th ed., 1958, pp. 661-663.)

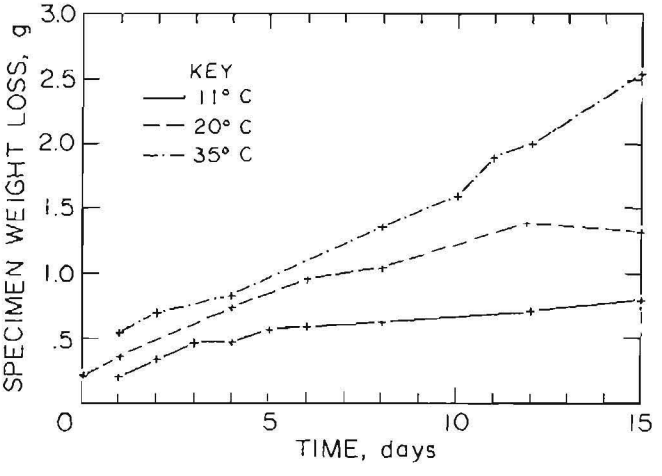

FIGURE 13. - Variation of the rate of gypsum dissolution with temperature. Static solution, 0.400 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

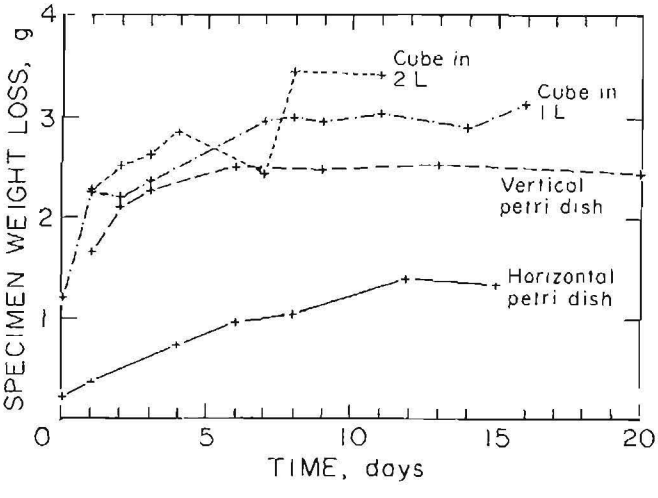

FIGURE 14. - The effect of surface orientation on gypsum dissolution. Static solution, 0.400 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

figure 12,[6] is constant for practical purposes. On the other hand, as shown in figure 13, the rate of dissolution increased at 35° C, compared with the room temperature rate, and decreased at 11° C. Although the difference in rate appears marked in the 15-day time span shown, the difference becomes insignificant when considered in the context of the 10-yr lifespan of a roof bolt.

Among the remaining variables, orientation of the gypsum surface had a significant effect upon the dissolution rate. In a third series of static tests, petri dish specimens were placed in 1-L solutions identical to all others except that the exposed gypsum surface was oriented vertically. The gypsum loss was much faster for these specimens, and saturation was complete in about 6 days, in comparison with about 40 to 50 days for horizontally exposed specimens. In similar tests, 5-cm cubes in 1-L solutions dissolved at nearly the same rate as the vertically oriented petri dish specimens, although the cubes had 103 sq cm of vertical surfaces and the petri dish specimens had only 67 sq cm. The effect of surface orientation is shown in figure 14. The vertically oriented specimens

[6]Seidell, A., and W. F. Linky. Solubilities of Inorganic and Metal Organic Compounds. Van Nostrand, New York, v. 1, 4th ed., 1958, pp. 661-663.

dissolved faster because gypsum diffusion occurred over a range of depths, and the heavy ions of gypsum descended toward the container bottoms as they separated, leaving the remaining solution at lower concentration gradients. In contrast, dissolution of the horizontally exposed specimens occurred at one depth and one concentration gradient.

Figure 14 also shows that the 5-cm cubes lost approximately the same weight in either 1 or 2 L of static water, indicating that the dissolution rate in static solutions is diffusion controlled. The cubes in 1-L solutions lost more than enough weight to saturate the solution, the excess depositing at the vessel bottoms. Not immediately apparent, the average calcium ion concentration in the 2-L solution was half as strong as that in the 1-L solution.

To demonstrate that small changes in surface area have little effect upon dissoluion, petri dish specimens with varying amounts of horizontally exposed surface area were placed in 1-L solutions and dissolved. The results are graphically represented in figure 15. In comparison, it is seen that orientation is a more important variable than surface area.

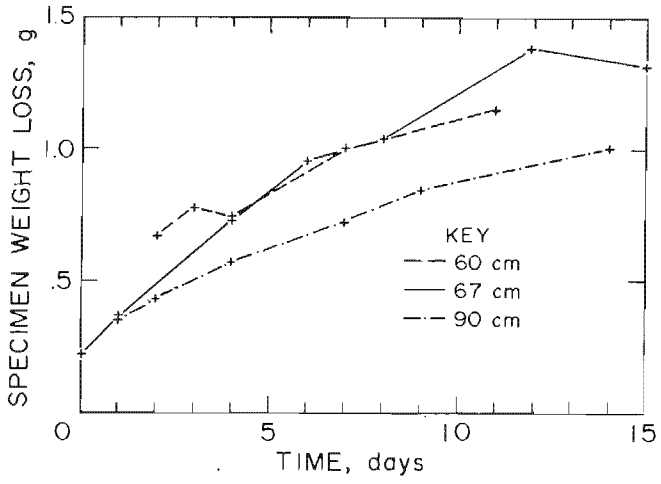

FIGURE 15. - The effect of surface area on gypsum dissolution. Static solution, 0.400 water-cement ratio, 1.5 pct accelerator, 100-g specimens.

COMPUTER MODELING OF GYPSUM DISSOLUTION

A computer model was developed to predict the weight loss of a 100-g gypsum mass at any flow rate slower than one that would cause physical erosion. The model also can be used to predict the weight loss of a sample in flowing solutions containing $CaSO_4$ and other sulfates. To use the model, the known factors must include the weight of the gypsum, the inflowing solution composition, and the flow rate of the solution.

The model is based on a system that is comprised of a mass of gypsum in a solution. Additional solution at a Ca^{2+} and SO_4^{2-} concentration, C_1, enters the system at a flow, F, and leaves the system at a concentration, C_2, and at the same flow, F. Gypsum is lost from the mass to the solution at a rate, R. The system is described by the equation

$$FC_2 = FC_1 + R. \qquad (2)$$

Then, solving for R,

$$R = F(C_2 - C_1). \qquad (3)$$

With flows slow enough so that C_2 is at or very close to saturation at a steady state, $C_{sat} \cong C_2$ and equation 3 becomes

$$R = F(C_{sat} - C_1). \qquad (4)$$

If W is the weight lost from the gypsum mass during time, t, then

$$\frac{dW}{dt} = R. \qquad (5)$$

Integrating equation 5 yields

$$\int dW = \int F(C_{sat} - C_1)dt \qquad (6)$$

or

$$W = F(C_{sat} - C_1)t. \qquad (7)$$

Equation 7 represents the simplest of environments and can be applied only to systems in which flows are small, on the order of 0.5 L per month or less. With such flows, at the end of 1 yr a mass of any size will have lost a maximum of about 13 g if the dissolving solution initially contains no Ca^{2+} or SO_4^{2-} ion concentrations.

Of more general interest, because of the possibility for greater damage, are faster flows in which C_2 is not saturated. For these flows, equations 4 and 7 cannot be used. The equation that most nearly matches the data is

$$R = R_0 \left[\frac{K_{sp} - [Ca^{2+}]\ [SO_4^{2-}]}{K_{sp}} \right], \quad (8)$$

where R_0 is an experimentally determined constant and represents the greatest possible dissolution rate obtainable; that is, the initial dissolution of a mass in a pure water solution occurring over an infinitesimal time. Most conveniently, R_0 will be in units of grams per day. K_{sp} is the solubility product for gypsum and is equal to 1.9593×10^{-9}. The terms $[Ca^{2+}]$ and $[SO_4^{2-}]$ represent ion concentrations and are in moles per liter. The entire bracketed quantity is a unitless number that runs from 0, in saturated solutions, to unity, in distilled water.

By substituting this term for R in equation 5 and integrating, an expression conceivably can be obtained that will be useful for all situations of gypsum deterioration except those involving erosion. However, the integration is not readily solved, but with a computer, multiple iterations can be processed to produce a nearly identical result. In this study, the iterations were made for systems with several flows at several ion concentrations.

The first and simplest system was composed of 100 g of gypsum and 1 L of water with no initial ion concentration and no exchange across the system boundary. The term R in equation 8 was then equal to R_0 when the system started. The term R_0 was determined in static dissolution tests in pure water by calculating the slope of the resulting dissolution-versus-time curve. By assuming a small initial time increment, the Ca^{2+} and SO_4^{2-} ion concentrations (which were equal) at the end of the increment were calculated by multiplying R by the time. These ion concentrations and the constant, R_0, were substituted into equation 8 to determine a new value for R. A second time increment was assumed, the new R value was multiplied by the time, and new values for ion concentrations were determined. The iterations continued to saturation. As shown in figure 16, the weight loss from the 100-g mass at each time icrement plotted against time produced a smooth curve. Figure 16 also shows that experimentally determined points closely agree with the model.

Systems with flows across the boundary required the use of equation 3 in addition to equation 8. The initial rate, R, was computed by using equation 8 and the same value for R_0 as above. With known values for R and F and $C_1 = 0$, the ion concentration, C_2, in the outflowing water at the end of the first time interval was computed through equation 3. The iterations were continued until steady-state conditions were reached, while weight losses were computed at each time increment as before. Figure 17 shows

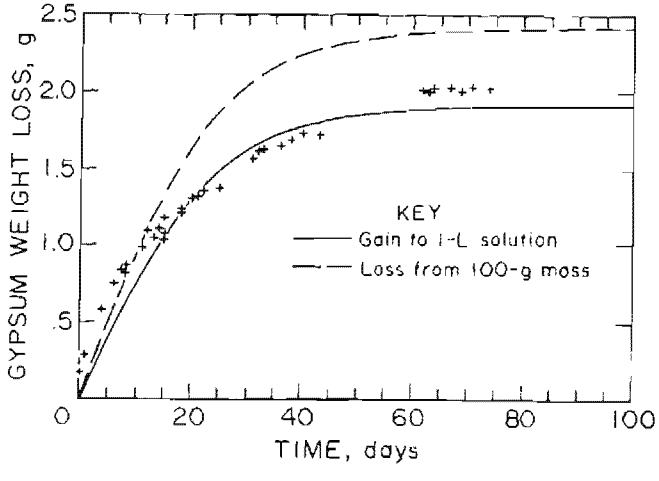

FIGURE 16. - Computer model of gypsum dissolution in a 1-L system with no flow or initial ion concentration. The lines represent the model, and the points represent the experimental determinations of weight loss.

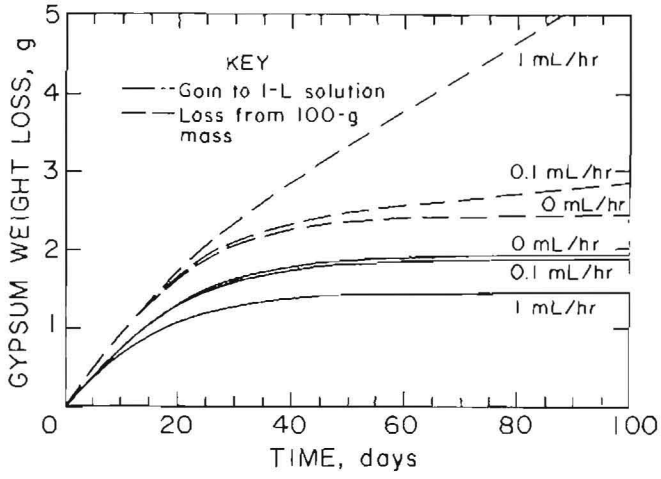

FIGURE 17. - Computer model of gypsum dissolution in a 1-L system with indicated flow but no initial ion concentration.

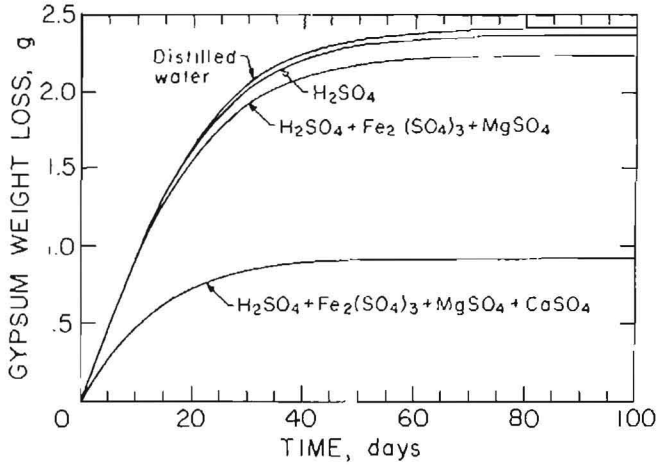

FIGURE 18. - Computer model of gypsum dissolution in a 1-L system with no flow and indicated initial ion concentrations. The ionic concentrations are given in more detail in table 2.

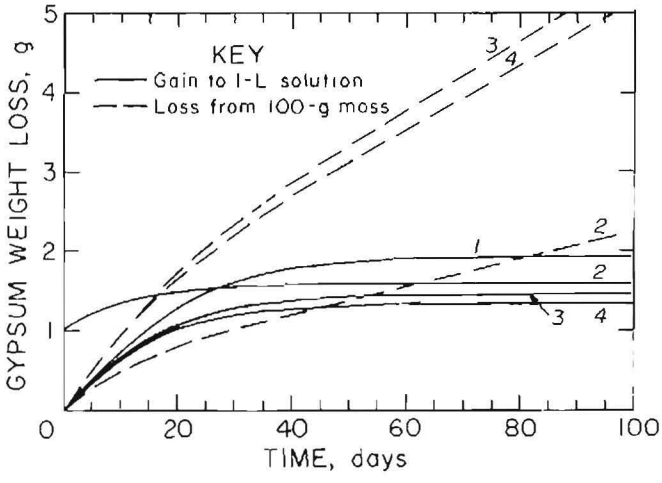

FIGURE 19. - Computer model of gypsum dissolution in a 1-L system with 1-mL/hr flow and indicated inflow ion conditions. The ionic concentrations are given in more detail in table 2. *1*, Distilled water, no flow; *2*, 1 g/L $CaSO_4$ + 100 ppm $Fe_2(SO_4)_3$ + 100 ppm $MgSO_4$ - H_2SO_4 to pH 3; *3*, distilled water; *4*, 100 ppm $Fe_2(SO_4)_3$ - 100 ppm $MgSO_4$ - H_2SO_4 to pH 3.

computed curves for flow rates of 0.1 mL/hr, for 1 mL/hr, and, as a comparison, for the static or zero flow rate shown in figure 16. The solid lines represent the concentration of gypsum in the outflowing solution (or in the system solution in the case of the static system), and the dashed lines represent the gypsum that is lost from the 100-g masses. Steady-state conditions in the flowing solutions occur at the straight line portions of the curves at less than saturation. As the flow is increased, steady-state conditions are realized earlier, in about 60 days at 0.1 mL/hr and 50 days at 1 mL/hr. At 0.1 mL/hr, the steady-state dissolution rate is 5.7×10^{-3} g/d, and at 1 mL/hr, the rate is 43×10^{-3} g/d. Since dissolution is independent of mass, these rates, or the rates for any other flow conditions, can be applied directly to any mass. In most practical situations involving systems containing more than 1 L, R_0 will not be altered appreciably.

As it was applied to the first two systems, the model was applied to systems that initially contained Ca^{2+} and SO_4^{2-} ions or in which inflows contained ions. Values for these concentrations were inserted in equation 8 and, where appropriate, for C_1 in equation 3. The concentrations that were selected were those listed in table 2. The iterations produced the curves shown in figures 18 and 19. Under zero flow conditions, as seen in figure 18, less material was lost as the Ca^{2+} and SO_4^{2-} concentrations in the initial solutions increased. Compared with gypsum in distilled water, the gypsum in a solution containing H_2SO_4, $Fe_2(SO_4)_3$, $MgSO_4$, and $CaSO_4$ lost about one-fifth less weight. Moreover, solutions with initial ion concentrations became saturated earlier.

Dissolutions also were computed for the concentrations in table 2 and a flow rate of 1 mL/hr. The weight lost under each condition is shown in figure 19 by the dashed lines, and the weight gain to the solutions is shown by the solid lines. Steady-state conditions are denoted by the straight-line portions of the curves.

CONCLUSIONS

Whether installed by slurry or by cartridge, gypsum-bonded roof bolts will be subject to dissolution in the presence of water. Although the wax that permeates the gypsum upon cartridge installation of a bolt occupies substantial volume, it will have little effect upon the dissolution. The rates of gypsum dissolution are slow in comparison with the rates of many other dissolvable substances, but when viewed within the context of the lifetime of a roof bolt, which may extend to 10 yr or more, the rates of gypsum dissolution are significantly fast. Within this context, of all the factors that have an influence upon dissolution, only the initial ionic concentration of the solution surrounding the roof bolt and the movement of the solution have significant effects.

If the dissolving solution initially contains Ca^{2+} or SO_4^{2-} ion concentrations at or above the solubility limit for gypsum, dissolution will not occur. With partial concentrations of these ions, dissolution will occur up to the solubility limit. Thus, in static solutions, damage to the gypsum cannot exceed 2.4 g/L. If the quantity of solution is small, this loss of gypsum will likely be insufficient to cause a corresponding loss to the load-carrying ability of the bolt. For example, if 5 L of static water surrounds a 2-ft bolt that is bonded with 300 g of gypsum, the maximum lifetime loss would be 12 g, or 4 pct of the total.

However, since miners cannot readily measure the flow at every roof-bolt site, any moisture in porous rock or rock that is fissured must be regarded as flowing water. Seepage or flows as slow as one drop per minute will amount to over 2 L per month. Moreover, since the initial ion concentration of water cannot be conveniently measured whenever a bolt is set, the water must be assumed to contain no ions. Consequently, at slow flow rates, the water leaving the environment surrounding a roof bolt will carry dissolved gypsum at the limit of solubility. At the above rate of one drop per minute, 4.4 g per month or 53.3 g per year of gypsum will be lost from the bolt. For roof bolts of any length, this amount is substantial. With faster flow rates the damage will occur faster, while with slower flow rates the damage will be slowed but not eliminated. For these reasons, gypsum-bonded roof bolts should be installed in dry roofs only.

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